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EFFECT OF INTAKE VALVE TIMING, DURATION STRATEGIES WITH SWIRL RATIO ON VOLUMETRIC EFFICIENCY OF SINGLE CYLINDER DIESEL ENGINE

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ABSTRACT

Small diesel engines are used for commercial transportation for rural and urban area due to cost and efficiency aspect. They are also the reason for pollution because of various reasons. This study aims to examine the effect of intake valve lift, timing and duration on four-stroke single-cylinder diesel engine's volumetric efficiency. One-dimensional thermodynamic simulation analysis is carried out for gas exchange and performance improvement study with various intake valve lifts, timing and duration along with swirl variation strategies. 1D simulation model is validated within 5% band with respect to engine's testing data. Early inlet valve opening (EIVO), closing (IVC) effect along with lift options are analyzed on engine's volumetric efficiency. IVO timings are varied from 31˚bTDC to 5˚aBDC with an interval of 6˚CA with duration varied from 50˚ HCE to 70˚ HCE with three lift options. Cylinder head swirl is reduced by 25%, while flow coefficient is improved by 10%. This along with optimum timing and lift combination produce 5–15% improvement in volumetric efficiency at wide engine speed range in simulation. Higher lifts, wide duration and lower lift with duration is beneficial for rated and intermediate engine speeds, respectively.

***KEYWORDS:** Valve Timing, Valve Duration, 1-Dsimulation, Intake Port Swirl, Volumetric Efficiency & Valve Lift*

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Original Article

INTRODUCTION

The Indian automobile industry is traditionally dominated by diesel engines, and when we discuss about urban and rural market, the domination of small diesel engines is clearly visible in the form of small and light commercial vehicle (LCV). These vehicles are fitted with small single and two-cylinder engines with simple and robust design features. Another major reason for their high demand is congested roads and heavy traffic density in cities. Market demand for vehicle with higher torque, power, BSFC with lower cost are the driving factors for vehicle manufacturers to develop high BMEP engines. For this, they replace single cylinder engines with two-cylinder engines and two-cylinder engines with three-cylinder engines. Along with market demands, the vehicle should also meet stringent emission legislation imposed by government. Implementation of latest technological improvements is limited in these vehicles and engines because of cost considerations. These engines require continuous improvements in performance and emissions front to meet upcoming stringent emission regulations with fuel economy requirements (Squaiella *et al*., 2013). There are various technological pathways to improve the performance and emission of engines, some of which are supercharging, turbo charging, variable compression ratio, variable intake system geometry, variable valve timing and lift, etc. (Miller *et al*., 2011). Considerable improvements have been done in after treatment system as well; however, sufficient conversion efficiency is still a big problem for them (Zammit *et al*., 2015).

Variable Valve Timing (VVT) has been applied to many engines in order to enhance the engine performance. Different valve timings, lifts and duration are required by the engine at different operating load conditions and speeds. Higher engine speeds require wider duration and higher lifts, while lower lifts and lesser durations are required at lower engine speeds. The VVT alteration can be individual or in combination, depends upon engine requirements and technological implementation. Phase shift and variable lift and duration are the two VVT systems that are used in petrol engines (Galindo *et al*., 2006). This also helps in flow distribution inside the combustion chamber and consequently the combustion quality, temperature, cylinder pressure, engine noise, starting, performance and emission of the engine (Sürmenet *et al*., 2017). Various studies have been carried out and implemented on gasoline and diesel engines, and OEM has adopted VVT/VVA systems on their engines. There is no production LCV engine available with VVT technology despite intensive research on this field. The upcoming emission norms for LCV application engines are very challenging and require significant improvement for in-cylinder flow and its distribution.

Opening of intake valves allow the air to flow into the combustion chamber, hence opening and closing timing of valves affect engine cycle efficiency (Benjas *et al*., 2009). Intake valve opening and closing, its lift and duration affect the combustion and emission from the engine. Volumetric efficiency also depends on combustion chamber geometry, mean piston speed, intake and exhaust system, environmental factors and port performances (Andrez Ambrozik *et al*., 2017). Volumetric efficiency increases with increase in IVO up to a certain limit after that it increases the backflow of exhaust gases, which reduces the volumetric efficiency sharply. Similarly, late IVC also allows more amount of air into the combustion chamber and affect volumetric efficiency up to a certain limit and after that limit, it forces inducted air back into the intake manifold. This reverse flow of air reduces the volumetric efficiency. Advancing IVO also allows gradual lift of intake valve, thus valve bouncing can also be reduced with proper timing.

Effects of various valve lift strategies on diesel engine through computer simulation and NOx emissions reduction with EIVO and LEVC have been carried out (Parvate Patil *et al*., 2004). EIVO and LEVC allows a portion of exhaust gases, goes to intake manifold due to higher pressure and comes back to combustion chamber during suction stroke and dilute the fresh air (Assanis *et al*., 1989). This phenomenon works as an internal exhaust gas recirculation (EGR) and reduces the fresh air availability (Munnannur, 2005). LIVO and LEVO are useful for reduction of unburnt hydrocarbon emissions. EEVO and EEVC also reduces the NOx emissions, however, they are detrimental to the engine performance (Goto *et al*., 2017 and Kohketsu *et al*., 1997).

Pierik *et al*. (2000) have developed a mechanical VVA system in which output cam lift can be varied from 0–9 mm using input cam lift. Further, they had verified this mechanism on a standard baseline European four-cylinder diesel engine and achieved BSFC improvement of 12% at idle speed, 7–10% at mid load and 0–3% at high load conditions. They also observed that the HC emissions degrade, while the NOx emissions improve with VVA. Ojeda *et al*. (2010) analyzed the effect of EIVC on the performance of a 6.8L V8 engine. The VVA mechanism is controlled, using an electro-hydraulic mechanism and performs the EIVC according to the engine requirement using a solenoid valve. The test results showed reduction in soot emission above 90% with fuel efficiency improvements of 5% and NOx levels below 0.2g/bhp-hr. Gurney *et al*. (2012) carried out 1D and 3D numerical simulation approach to study the effect of EIVC and LIVC on a 4-valve engine. They concluded that the EIVC and LIVC reduce the volumetric efficiency of the engine and drastically reduce the soot emissions during tests. Lancefield *et al*. (2000) built a model to simulate and predict engine performance using VVA mechanism with cyclically increased and decreased angular speed of the cam. They have observed that EIVC

and LEVO both decreased the BSFC of the engine by approximately 2.3% during simulation. The results also showed improvements in torque with EIVC by 6.3–8.2% and LEVO by 8.6 to 12.6%.

The in-cylinder fluid motion in internal combustion engines is also an important factor controlling the combustion process. It governs the fuel-air mixing and burning rates in diesel engines. The fluid flow, prior to combustion in internal combustion engines, is generated during the induction process and developed during the compression stroke. Therefore, a better understanding of fluid motion (Gafoor *el al*., 2015) during the induction process is critical for developing engine designs with the most desirable operating and emission characteristics (Broatch *et al*., 2017).

At low speeds, in gasoline engines, the pumping losses are much greater than those of diesel engines because of the throttle intake system. In diesel engines, load control is obtained by regulating the quantity of fuel injected (Wei *et al*., 2013). Diesel engines do not have a throttle to control the air-fuel mixture. Thus, due to the absence of the throttle valve, pumping losses are much less at part load condition.

Current work is a study of simulation strategy to evaluate the impact of intake valve timing, duration and lift on engine performance parameter for a modern light duty, single-cylinder diesel engine. Numerical simulations were carried out by means of a commercially available 1D software GT-Power and a predictive combustion model was adopted in order to properly evaluate the impact of different VVT strategies.

EXPERIMENTAL TEST SETUP

Baseline engine performance is measured on an engine dynamometer with in-cylinder pressure measurement system. Crank Angle (θ) and Cylinder Pressure (P) is captured and used as an input data along with engine specification mentioned in Table-1 for 1D simulation model along with tested data from engine dynamometer is used for calibration and validation of 1D simulation model of the engine for performance parameters. The flow in GT-Power is based on a one-dimensional Navier-Stokes equation. Scalar equations are solved based on finite volumes, mass flow at the boundaries. 1D simulation model is calibrated with engine test performance data within 5% band in terms of performance (Ref: Appendix-A), however, correlation of NOx emission with the band of 5% tricky situation, as it is underpredicted over higher engine speeds, thus bringing in adequacies in the model and cast doubt on predictions; however, quantitative agreements appear reasonable and correlated within 10% band. Exhaust gas temperature is correlated with testing data and was found to be within calibration band of 7%. Based on this calibration, engine performance is predicted for various timings, duration and lift options for performance enhancement and emission reduction. Valve lift and timing data is measured on baseline engine with the help of gauges. All the performance parameter, Power, Torque and BSFC values are obtained and compared with the tested data. The comparisons of data are shown below:

Table 1: Engine Specification

Type	Four stroke, Air cooled, single cylinder, CI engine
Fuel	Diesel
Number of cylinders	One
Bore/Stroke	1.146
Compression ratio	19±0.5
Rated Power	5.5 kW @ 3600 rpm
Rated Torque	18 Nm @ 2000–2400
Valve timing	Inlet Valve Opening (IVO) : 5.5° before TDC
	Inlet valve closing (IVC) : 24° after BDC
	Exhaust valve opening (EVO):23° before BDC
	Exhaust valve closing (EVC) :7° after TDC

	Valve Last 0.6–0.7 mm
	Max Lift: 7.6 mm

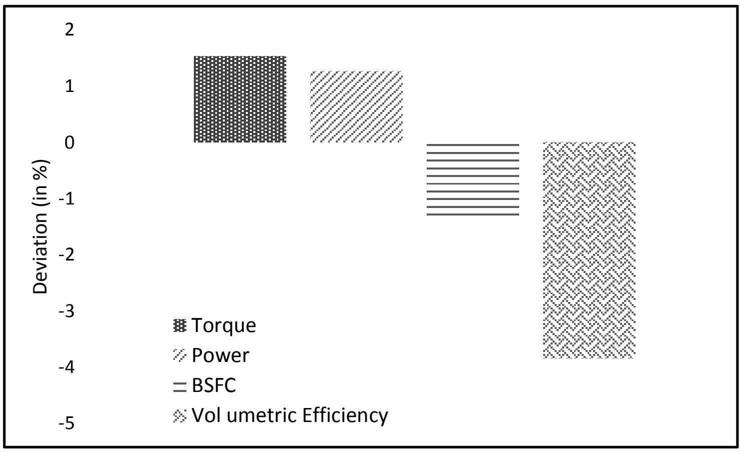

Figure 1: Deviation in Engine Testing and Simulation Data for Performance Parameter.

Above figure 1 show a good correlation of simulation model with testing data. For Power and Torque values obtained from simulation are slightly higher and BSFC is also better compared to baseline engine testing values, however; volumetric efficiency is lower than the baseline values. This is because of the difference between the test conditions for simulation and actual test bed. It remains constant for simulation, however, varies slightly for actual engine testing, also friction between the two is varying.

VALVE TIMING AND LIFT

Intake valve opening (IVO) and Intake valve closing (IVC) timings are varied from its initial values of 11°bTDC and 37°aBDC in both the direction at interval of 2–5˚ Crank angle with valve lift options of 7 mm to 9.1 mm are also tried out to analyze the effect. Figure 2 shows the typical opening and closing pattern for an IC engine.

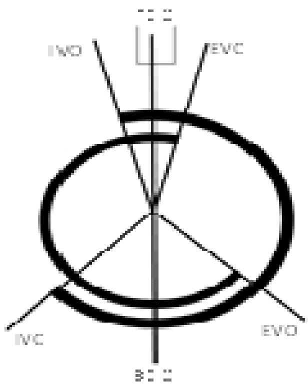

Figure 2: Intake and Exhaust opening and closing Pattern for IC Engine.

Initially, early Intake valve opening option is tried out to with 50° Half Cam event (HCE) and 7-mm valve lift, i.e., the total cam opening duration is 200° crank angle with IVO option varies from 31° bTDC to 5° aTDC are simulated. This has shown a negative effect on volumetric efficiency, as it shrinks to 54% only, hence 50° HCE duration option is not

considered for further simulations and 55° to 70° HCE with 7 to 9 mm lift options were simulated. Similarly, baseline engine's cylinder head is modified for lower swirl and higher flow coefficients. Effect of three sets of swirl and flow coefficient values will also be discussed in further sections. Table 2 shows the different options tried out for opening, closing, lift and duration for simulation model.

Table 2: Various Valve Opening, Closing, Lift and Duration Options used in for Simulation

Intake Valve	Max	Min	Interval
Opening	31° bTDC	3° bTDC	2° Crank Angle
Closing	5° aBDC	90° aBDC	2° Crank Angle
Lift	9 mm	7 mm	0.6–0.7 mm
Duration	70° HCE	50° HCE	5° HCE
Swirl	2.45	1.9	□.95
Flow Coefficient	0.34	0.31	0.01–0.02

RESULTS AND DISCUSSIONS

Effect of each parameter (IVO, IVC, Valve lift, duration and Swirl) on engine performance and emission is analyzed individually, while keeping other parameters as constant for initial trails, and results are compared with baseline engine testing data. Based on these analyses, various strategies for intake valve opening, closing, lift and swirl ratio are evaluated for various engine speeds and used for engine testing.

Effect of Valve Timing and Duration

The effect of Intake valve with 7 mm lift and 50° HCE duration on performance parameters is analyzed. Intake valve opening is varied from 31° bTDC to 3˚ bTDC. Effect of IVO Vs Volumetric efficiency is shown in Figure 3. It depends on IVO angle and total valve duration. As duration increases, volumetric efficiency increases till certain valve duration and after that it starts decreasing, here. In this case, it starts decreasing after 60° HCE. For lower duration, it is beneficiary that IVO should be close to TDC; however, for longer valve duration, IVC also plays a significant role in deciding the intake air quantity. Here, it varies from 54% to 70% for advance IVO with wide opening valve duration, however, remains flat for all IVO options at 60° HCE. As the opening is shifted from advance IVO towards TDC (from 31˚bTDC to 3˚bTDC), there are marginal changes in Torque, Power and Volumetric efficiency (Figure 6); however, BSFC is improved for higher engine rpm at advanced IVO options with slight increase in exhaust gas temperature. As we advance the IVO timing, higher advancing gives backflow of exhaust gases into the intake port and manifold, and during suction stroke, these gases again come back to combustion chamber along with fresh air. As the IVC shifts towards BDC, these options further restrict the quantity of air inside combustion chamber. The cylinder pressure and the volume inside the combustion chamber is also lower (Figure 4) for advance IVO. The start of combustion also varies as per IVO timings and engine speed (Figure 5), where combustion starts earlier for lower engine speed, however, it gets delayed for higher engine speed. Reason for this early start is higher amount of air coming into the combustion chamber, as lower engine rpm gives slightly more time for air to enter into the combustion chamber and inertia effect also helps in feeding more air. The phenomenon gets reversed, as IVO shifts toward TDC for same duration, as equivalence ratio is minimum for the burnet mass fraction Moreover, as the IVO shifts towards TDC, the start of ignitions will also vary due to change in compression ratio, as the quantity of air varies. Even though the equivalence ratio is lower for rated torque speed compared to rated speed; however, the in-cylinder pressure is higher and combustion starts early.

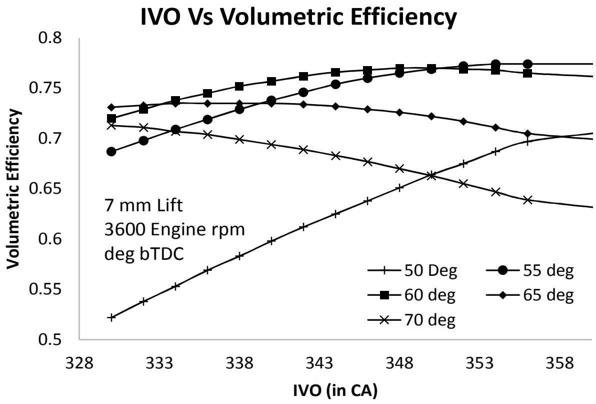

Figure 3: IVO Vs Volumetric Efficiency for 3600 Engine rpm and 7 mm Lift.

7-mm lift with 220˚ crank duration and advance IVO have shown volumetric efficiency improvements at wide engine speed range; however, the effect is higher at intermediate and higher engine speeds compared to lower engine speed. Effect of IVO timings is lower at rated speed; however, shifting of the IVO towards TDC at various speeds has positive effect on engine parameter, as duration is constant. During advanced IVO, the IVC shifts towards bBDC and hence restrict the quantity of air coming inside due to inertia, and internal EGR effect also reduces availably of fresh air. The effect on BSFC (Figure 6) is mixed for these valve timings and duration, as it deteriorates at some engine speed and improved at others, however, these improvements are very minor. The quantity of air and its pressure and temperature inside the combustion chamber affect the start of combustion timing and heat release rate. Further increase in the duration to 60˚ HCE (240˚) with advanced IVO has deteriorated the volumetric efficiency (Figure 8) at higher engine speeds, however, it has slightly improved at lower and intermediate engine speeds, as intake time duration becomes small for higher engine speed. Reverse flow of exhaust gases and higher inlet temperature are the factors for reduced volumetric efficiency along with penalty in BSFC with higher duration. The reason for sudden drop in volumetric efficiency in 1400–1800 engine speed is observed at all iterations, probable reason for this drop being a very small engine. The response in speed is so fast that the quantity of air available is limited. This needs to be accessed for various factors; however, we are getting good correlations at all other speed, hence exclusions can be done for one speed point.

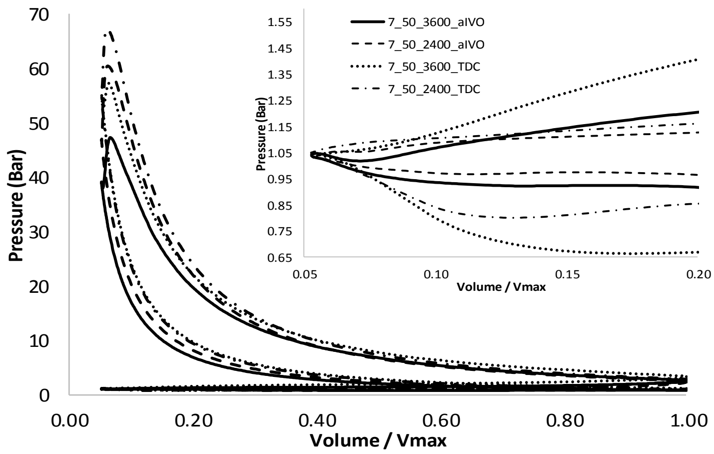

Figure 4: Pressure Vs Volume Curve for Various IVO options with 50° HCE & 7 mm lift for Advance IVO and IVO at TDC.

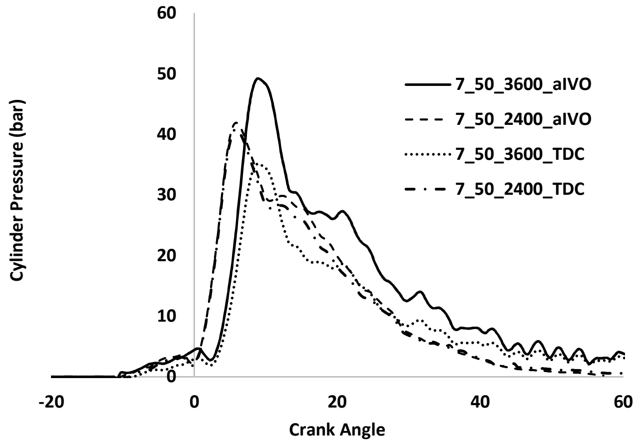

Figure 5: Cylinder Pressure Vs Crank Angle Curve for Various IVO options with 50° HCE & 7 mm lift for Advance IVO and IVO at TDC.

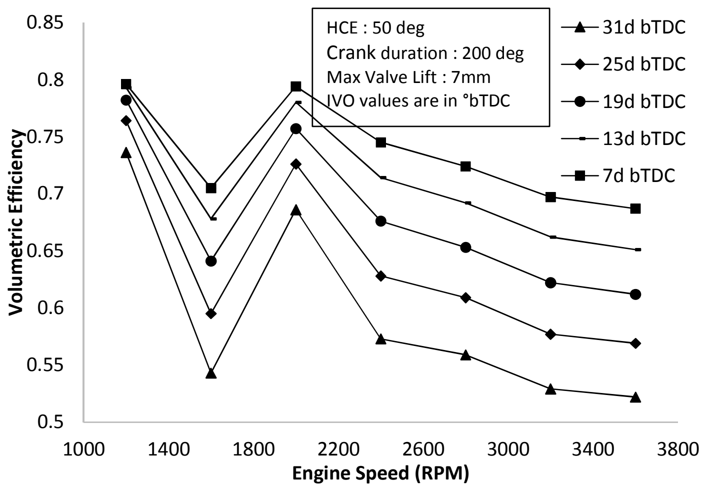

Figure 6: Comparison of Engine Speed Vs Volumetric Efficiency Curve for various IVO Options with 50° HCE & 7 mm Lift.

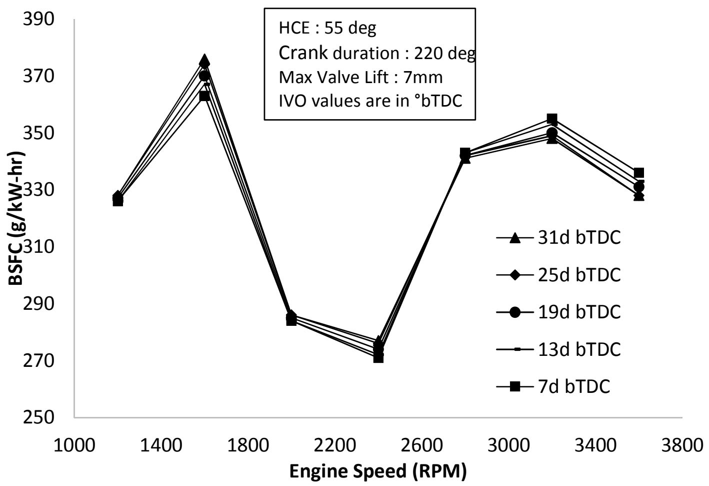

Figure 7: Comparison of Engine Speed Vs BSFC Curve for various IVO Options with 55° HCE & 7 mm Lift.

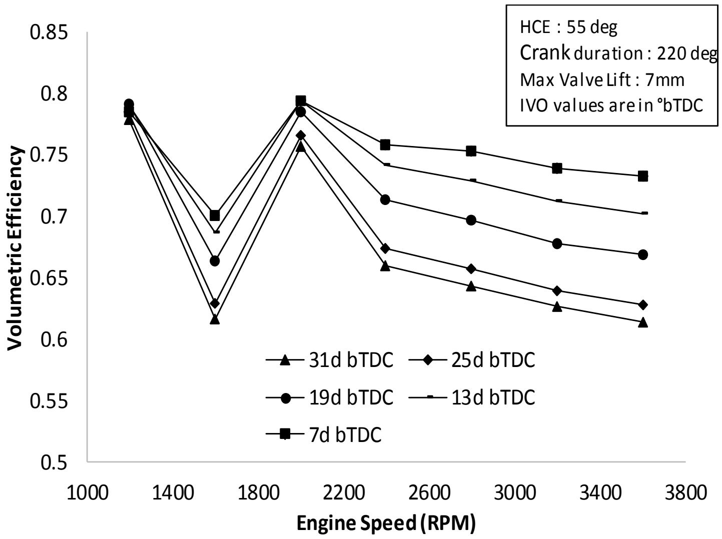

Figure 8: Comparison of Engine Speed Vs Volumetric Efficiency Curve for various IVO options with 55° HCE & 7 mm Lift.

Further increase in valve duration to 65˚ HCE and 70˚ HCE (260˚ CA and 280˚ CA) reduces the volumetric efficiency (Figures 10–11). In this case, as the IVO shifts towards TDC, efficiency decreases. Retarded IVO increase the inertia effect, hence it takes longer time for the charge to enter the combustion chamber and longer duration increases the backflow. Thus, a portion of fresh air goes back to manifold, thereby reducing the amount of air available in the combustion chamber. The reason for further reduction of volumetric efficiency with higher valve opening duration when compared with the lower valve opening duration is higher reversed flow during valve overlap period and intake backflow during piston upwards movement from BDC to TDC.

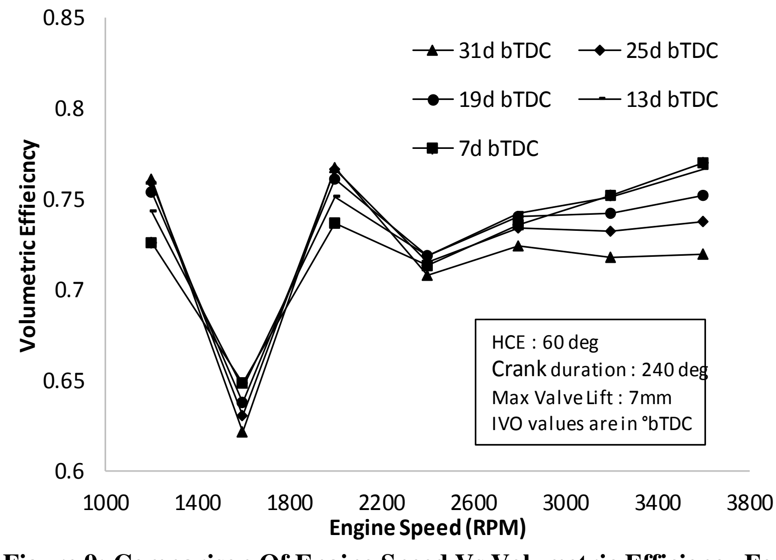

Figure 9: Comparison Of Engine Speed Vs Volumetric Efficiency For Various IVO Options With 60° HCE & 7 Mm Lift.

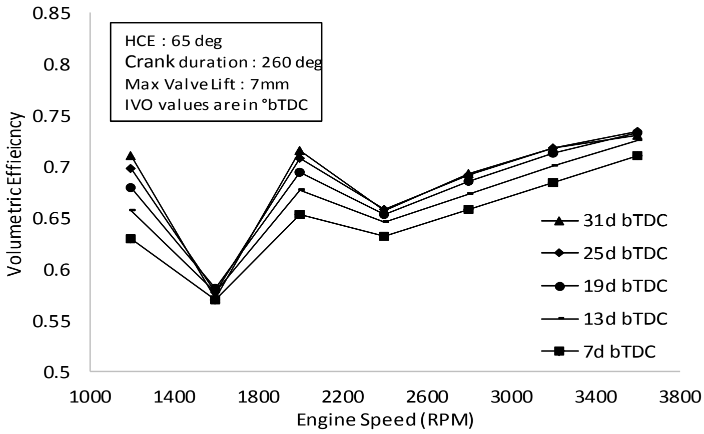

Figure 10: Comparison of Engine Speed Vs Volumetric Efficiency for various IVO Options with 65° HCE & 7 mm Lift.

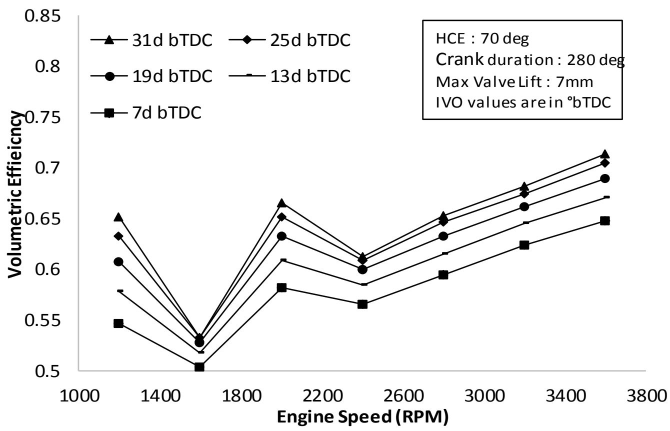

Figure 11: Comparison of Engine Speed Vs Volumetric Efficiency for various IVO Options with 70° HCE & 7 mm Lift.

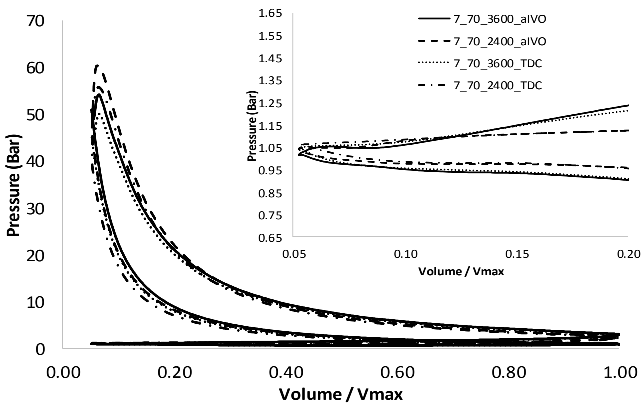

Figure 12: Pressure Vs Volume Curve for Various IVO options with 70° HCE & 7 mm Lift for Advance IVO and IVO at TDC.

Effect of high duration with advanced IVO and IVO at TDC options on pressure volume diagram for 7 mm lift with 70˚ HCE shows minimum residue and trapped volume, as shown in Figure 12. Advanced IVO with higher duration becomes normal IVC timing; however, for retarded timing, IVC shits close to TDC, this further increases the backflow of fresh air availability.

Option of 50˚ HCE (200˚ CA) is limited for lower valve lift of 7 mm and not used for higher lifts and lower duration, as it leads to higher valve velocity, acceleration and jerk. In addition, it can create excessive wear to cam during testing, considering proto engine assembly.

Effect of Valve Lift, Timing and Duration

Changing the lift from 7 mm to 7.6 mm, which is existing baseline engine's lift; However, with different duration, opening strategies are tried with 55˚ HCE (220˚ CA) to 70˚ HCE (280˚ CA) with an interval of 5˚ HCE (20˚ CA), maintaining IVO patters as per previous simulations. Practical limitation of valve-to-piston clearance is of minimum 1% of bore in diesel engines. It is not possible to advance the IVO further to 31˚ Btdc, as it needs valve pocket depth of more than 1 mm, which affects effective compression ratio of the engine. The effect of 7.6 mm lift with various IVOs and durations are shown in Figure 13. Lowest duration with advance IVO option has minimum volumetric efficiency. Increase in IVO position increases volumetric efficiency along with valve duration until a threshold value, and it starts decreasing after that value. Similarly, volumetric efficiency increases till 60 ˚HCE cam duration and starts decreasing after that. Longer duration timings with retarded IVO provide privilege of late IVC. It is responsible for higher backflow of fresh air into intake manifold and thus reduces the air quantity and volumetric efficiency.

7.6 mm lift with 55˚ HCE (220˚ CA) has uniform volumetric efficiency except at intermediate speeds; however, with increase in duration from 55˚ HCE to 60˚ HCE have complex effects (Figures 20 and 21). Advancing the IVO at higher engine speed improves volumetric efficiency compared to lower HCE; however, as IVO shifts towards TDC, volumetric efficiency reduces. Volumetric efficiency of the engine also increases by 9.7% at rated engine rpm when compared with baseline engine; however, there is slight decrease of volumetric efficiency at low engine speed, as shown in Figure 14. BSFC values at rated rpm is slightly higher than the baseline engine, as we move towards TDC. As intake valve opens 31°bTDC, there will be loss of fresh charge due to higher overlap of intake and exhaust valve. Certain amount of fresh charge goes with the exhaust gases when the piston moves towards TDC. This ensures availability of only fresh charge in the combustion chamber, hence the exhaust gas temperature is slightly lower and reverse happens as IVO shifts towards TDC. There is marginal improvement in Power and Torque, also when opening of Intake Valve shifts towards TDC. . Lower engine speed with wide opening duration has lower rate of air pressure drop and consequently lower incoming air velocity affects the quantity of air.

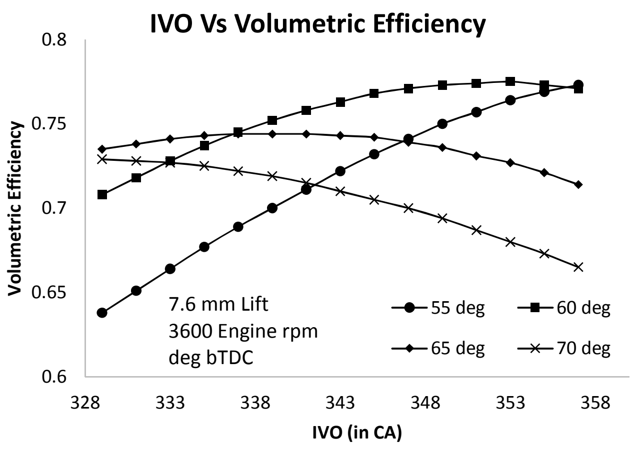

Figure 13: IVO Vs Volumetric Efficiency for 3600 Engine rpm and 7.6 mm Lift.

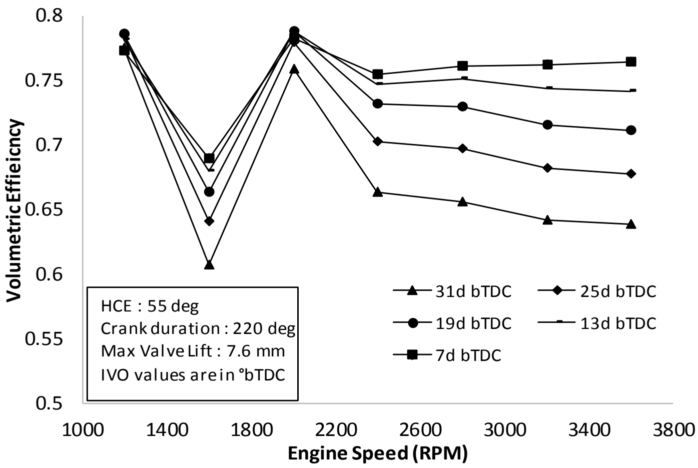

Figure 14: Comparison of Engine Speed Vs Volumetric Efficiency for various IVO Options with 55° HCE & 7.6 mm Lift.

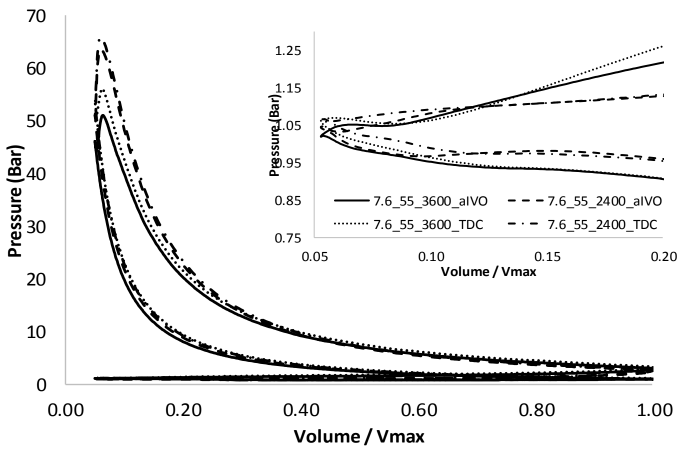

Figure 15: Pressure Vs Volume Curve for Various IVO Options with 55° HCE & 7.6 mm Lift for Advance IVO and IVO at TDC.

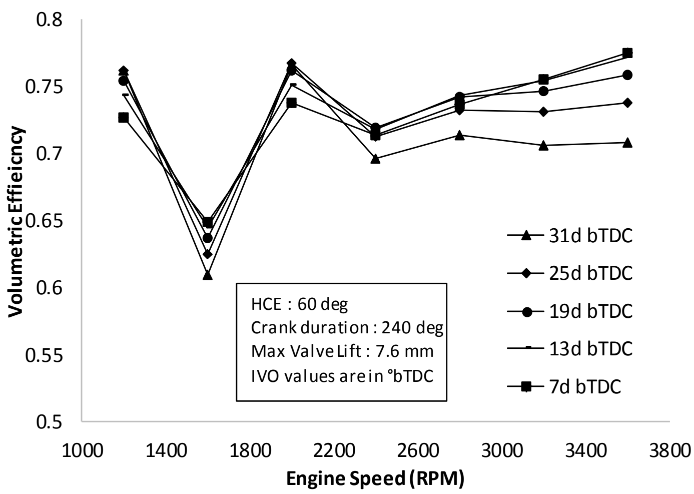

Figure 16: Comparison of Engine Speed Vs Volumetric Efficiency for Various IVO Options with 60° HCE & 7.6 mm Lift.

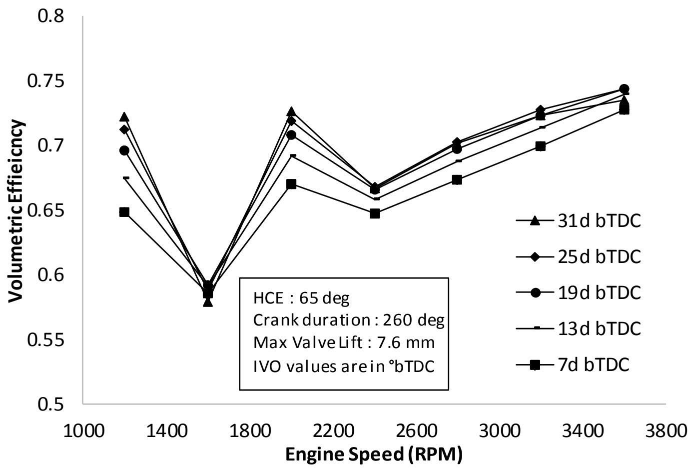

Figure 17: Comparison of Engine Speed Vs Volumetric Efficiency for various IVO Options with 65° HCE & 7.6 mm Lift.

Further increase in duration to 65˚HCE and 70˚HCE (260˚ CA and 280˚ CA) reduce volumetric efficiency as compared to 55° and 60° HCE, as the effect of retarded IVO gets reversed with the advancement of IVO increase in the volumetric efficiency (Figures 17 and 18). In these cases, advancement of IVO has better volumetric efficiency; reason for lower volumetric efficiency of retarded IVO is lower inertia effect and reversed flow reduces the amount of air availability in combustion chamber.

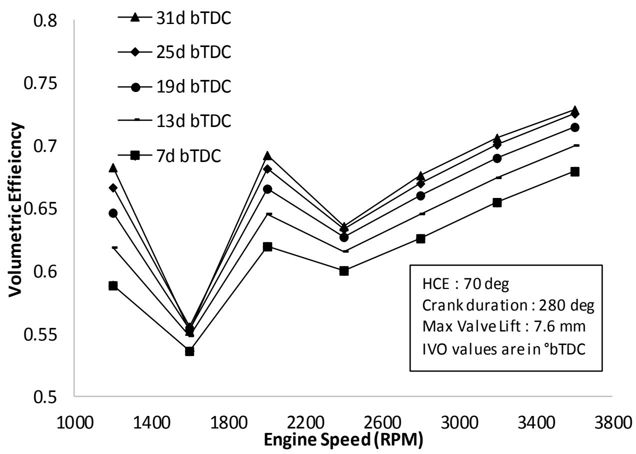

Figure 18: Comparison of Engine Speed Vs Volumetric Efficiency for Various IVO Options with 70° HCE & 7.6 mm Lift.

Further increase in lift from 7.6 mm to 8.3 mm with different durations and opening strategies are tried from 55˚HCE (220˚ CA) to 70˚ HCE (280˚ CA) with an interval of 5˚ HCE (20˚ CA), while IVO patterns are the same, as per previous simulations. An 8.3 mm lift with 55˚ HCE (220˚ CA) has uniform volumetric efficiency, varying from 60% to 78%, as shown in Figure 19. It follows the same trend as per previous cases wherein volumetric efficiency increases with duration until threshold point starts decreasing after certain duration. Increase in duration from 55˚ HCE to 60˚ HCE have complex effects. Advanced IVO at higher engine speed volumetric efficiency improves compared to 55˚ HCE: however, retarded IVO provides better efficiency at higher engine speed. Lower engine speed with wide opening duration has lower rate of air pressure drop and consequently lower incoming air velocity affects the quantity of air. As IVO angle shifts towards TDC for 8.3 mm lift, there will be benefit in terms of volumetric efficiency (Figure 21) and BSFC, while the effect of IVO and lift is needed to be further investigated for Torque and Power, as there is very marginal improvement and is not

as anticipated. The maximum improvement is achieved at 7°bTDC with improvement in volumetric efficiency, which is 9.3% at rated speed, while minimum at idling speed. Effect of further increase in duration to 60° HCE on volumetric efficiency is shown in Figure 20. It is clear from Figure 21 that wide opening of Intake valve with early opening does not improve the volumetric efficiency unless EIVC.

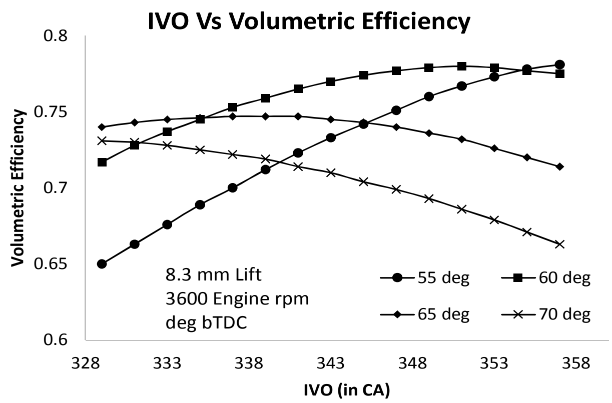

Figure 19: IVO Vs Volumetric Efficiency for 3600 Engine rpm and 8.3 mm Lift.

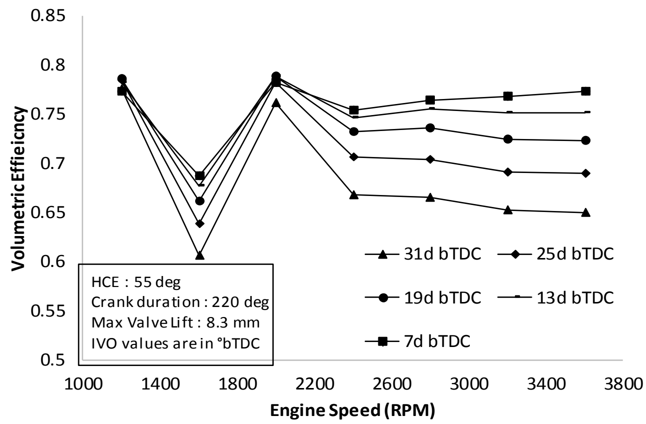

Figure 20: Comparison of Engine Speed Vs Volumetric Efficiency Curve for various IVO Options for with 55° HCE & 8.3 mm Lift.

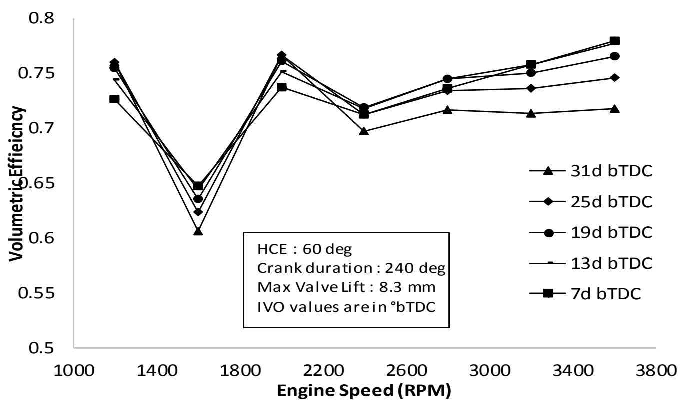

Figure 21: Comparison of Engine Speed Vs Volumetric Efficiency Curve for Various IVO Options with 60° HCE & 8.3 mm Lift.

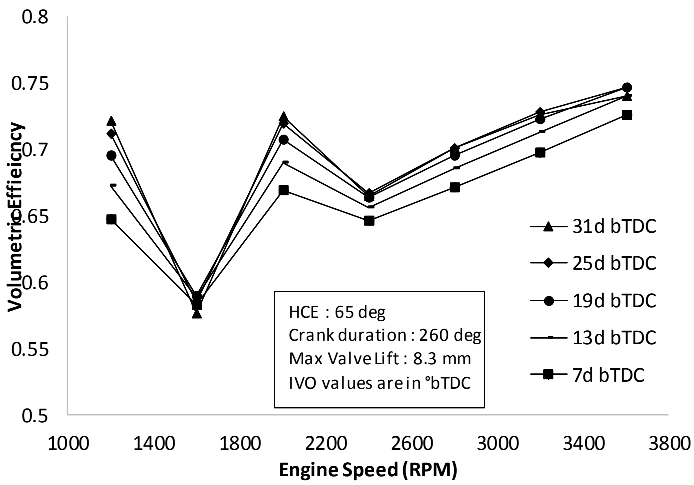

Figure 22: Comparison of Engine Speed Vs Volumetric Efficiency Curve for Various IVO Options with 65° HCE & 8.3 mm Lift.

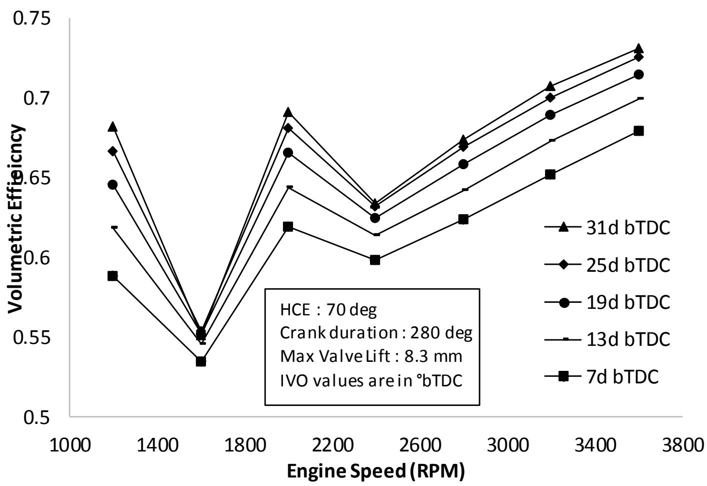

Figure 23: Comparison of Engine Speed Vs Volumetric Efficiency Curve for Various IVO Options with 70° HCE & 8.3 mm Lift.

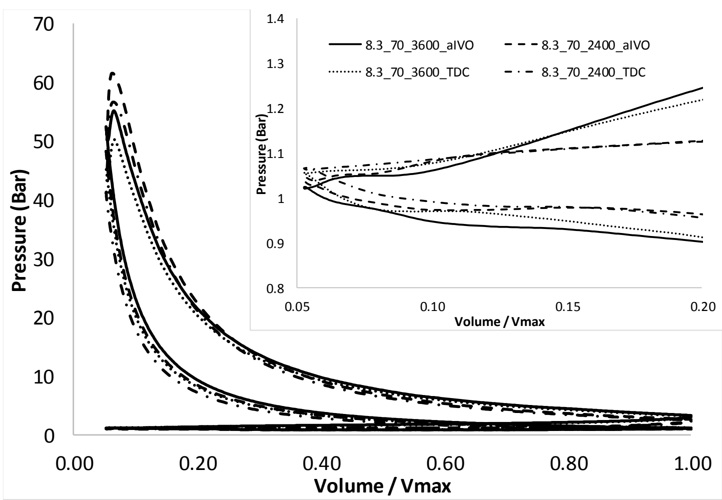

Figure 24: Pressure Vs Volume Curve for Various IVO Options with 70° HCE & 8.3 mm Lift for Advance IVO and IVO at TDC.

Further increase in duration to 65° and 70° HCE with 8.3 lift is also investigated, but the results are not discussed in detail, as the effect does not improve the performance parameters and volumetric efficiency. The pressure inside the cylinder is also less, which shows no residue or trapped volumes after combustion, thus temperature rise due to this is minimum; however, work done in recompression and uncompression in these masses is very less. Reason for this is as the lift increases, the area between Valve and Seat increases, and this allows more amount of air to enter inside the combustion chamber; however, this area reduces the velocity of incoming area, considering the inlet suction pressure remains the same. Hence, the benefit that has to be derived is not achieved at higher engine speed. Figure 21 shows the P-V diagram for 8.3 with advance IVO and IVO at TDC. It does not show residue and trapped gases, hence the piston work for escaping is reduced; however, the peak pressure is lower due to internal EGR and availability of air. Performance of Intake valve lift of 9 mm with 55° HCE on volumetric efficiency is shown and discussed in short, as the effect is in reverse mode. This combination of lift along with IVO of 7°bTDC has shown best results in terms of volumetric efficiency with volumetric reaching approximately 78%.

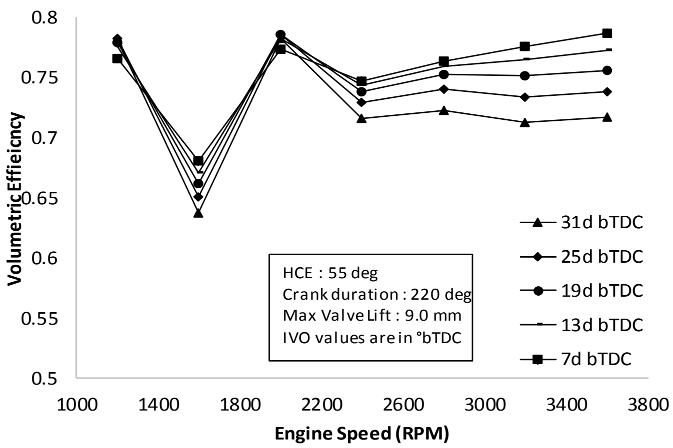

Figure 25: Comparison of Engine Speed Vs Volumetric Efficiency Curve for various IVO Options with 55° HCE & 9.0 mm Lift.

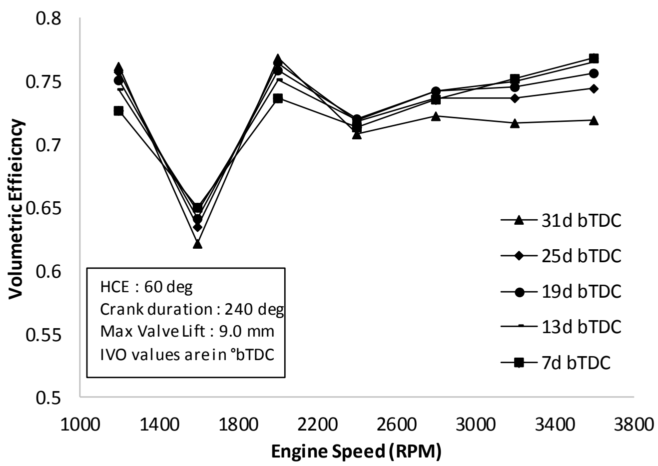

Figure 26: Comparison of Engine Speed Vs Volumetric Efficiency Curve for various IVO Options with 60° HCE & 9.1 mm Lift.

Increasing lift beyond a certain limit is not helping, as it reduces the incoming air velocity and thus the rate of pressure rise inside the cylinder due to high intensity incoming air decreases. Higher duration also starts reducing the quantity of air due to higher reverse flow at late IVC and backflow due to higher overlap.

Effect of Swirl Ratio and Flow Coefficient

Cylinder head swirl is modified to bring it to lower level and to reduce the port resistance to increase the flow coefficient of the port. Effect of Intake port swirl and flow coefficient is discussed on the engine performance and volumetric efficiency. All iterations carried out in simulation were with baseline cylinder head having swirl and flow coefficient values of 2.45 and 0.314, respectively. The experiments are performed on steady state swirl rig with AVL paddle wheel measurement principle. The cylinder head swirl is modified experimentally with the help of local machining and additional of metallic putty locally to reduce the port resistance in flow and to increase flow coefficient. Comparison of Swirl Ratio and flow coefficient is shown in Figure 27. Swirl and flow coefficient values of cylinder head is 1.91 and 0.345, respectively, which shows reduction of Swirl ratio by 22% and Flow coefficient improvement by 10%. Improvement in the flow coefficient is majorly for the higher lift regions, while swirl ratio is reduced for all the lift. This modified cylinder head performance along with the above-mentioned timing is analyzed in the next section.

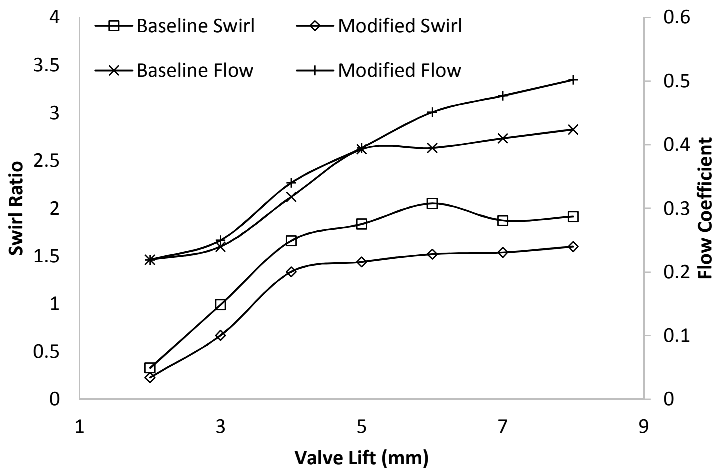

Figure 27: Comparison of Swirl Ratio and Flow Coefficient for Baseline and Modified Cylinder Head.

Effect of VVT and Flow Coefficient

By combining all the points of the valve timing, duration and lift strategy wherein improvements were observed in the engine volumetric efficiency at wide engine speed, the volumetric efficiency will be higher for lower engine speed, however, slightly better at rated engine speed, as shown in Figure 28. These optimized points with modified flow coefficient shows further improvement in the volumetric efficiency. It reaches approximately flat in wide speed range and the effect is highest at intermediate engine speeds. The improvement varies from 2–15% with maximum at torque speed.

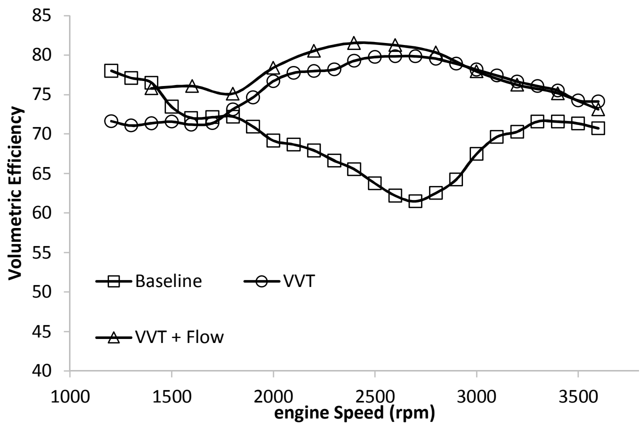

Figure 28: Comparison of Engine Speed Vs Volumetric Efficiency for Baseline and Optimised Combination.

It is clear that with modification in swirl and flow coefficient, there is positive effect on volumetric efficiency. Further analysis for optimization of exhaust valve timing will be the scope for future work.

CONCLUSIONS

The effect of each parameter (IVO, IVC, valve lift and Swirl) on engine performance and emission is analyzed individually, while keeping other parameters as constant for initial trails, and the results are compared. Advance opening of Intake valve with lower lift and duration have negative effect on engine performance and volumetric efficiency. As IVO shifts towards TDC, this negative effect on volumetric efficiency reduces and it comes into the positive zone. With IVO close to the TDC, for the higher valve duration, the effect of LIVC is achieved and has a positive effect on volumetric efficiency.

Increase in Valve lift also has positive effect on engine performance with lower opening duration: however, increase in opening duration can hamper the engine performance and have negative effect on volumetric efficiency and BSFC. Swirl ratio reduction and increase in flow coefficient also have positive impact on engine volumetric efficiency; however, this effect is higher for higher lift and lower for lower lifts.

Optimizing intake valve timing, lift and duration increase overall engine volumetric efficiency by 9.3% with the maximum increase of 22% at 2800 engine rpm. This also has an effect on maximum Torque value by 10.5% compared to baseline engine. Further optimization is required in exhaust valve timing, duration and lift to get advantage of Torque, Power, BSFC, volumetric efficiency and emission.

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APPENDIX-A

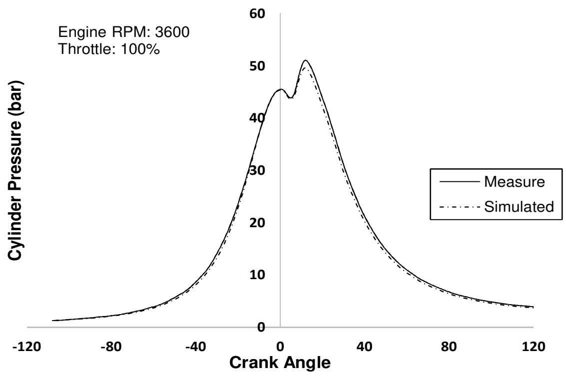

Figure 1: Comparison of Crank Angle and Cylinder Pressure for 3600 Engine rpm.

Figure 1 to figure 3 shows the P-θ values for measured and simulated results for three different engine speeds (3600, 2400 and 1200). In the mentioned Figures 1–3, for higher engine rpm, this correlation is good; however, for lower rpm the correlation is within acceptable limit.

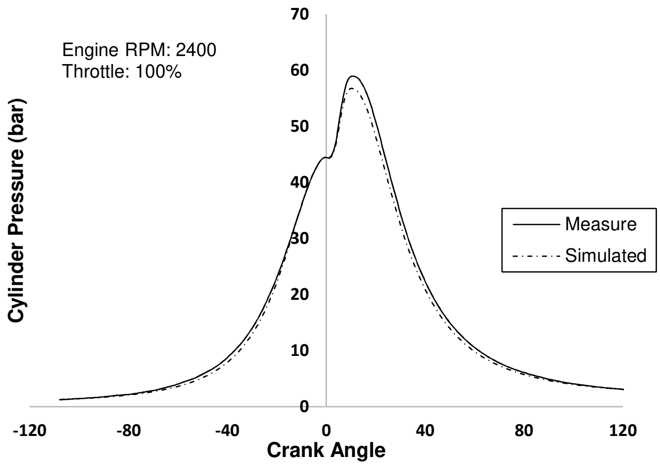

Figure 2: Comparison of Crank Angle and Cylinder Pressure for 2400 Engine rpm.

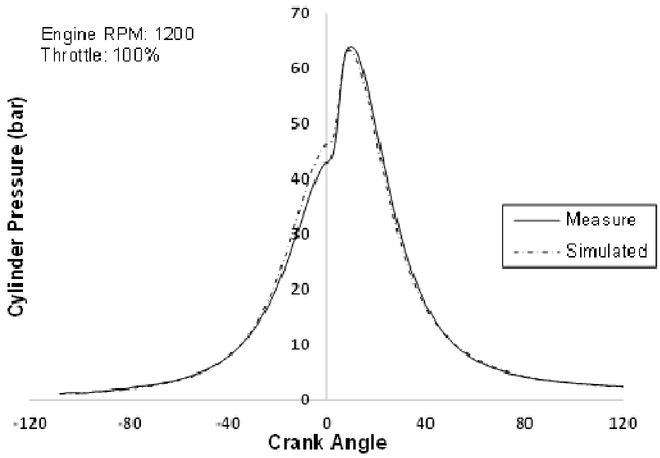

Figure 3: Comparison of Crank Angle and Cylinder Pressure for 1300 Engine rpm.

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Ashish Jain, currently working as a Manager in Power train Engineering Department at *The Automotive Research Association of India*, Pune. He did post-graduation from Vellore Institute of Technology, University, Vellore. He involves in various engine design and development projects for off-road and tractor application. He is also an active member of SAE India and published papers in SAE International in SIAT and FISITA events. His area of expertise is Cylinder Head, Intake and Exhaust port design, testing and optimization, Valve train design and development.

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Dr. S. S. Thipse has done his Master's in Thermal sciences from Bradley University, USA and his Ph.D. from New Jersey Institute of Technology in the field of Alternative Fuels Combustion. He has Research experience of over 20 years in the development of Alternative Fuel engines and vehicles, and is working in the capacity of deputy director at ARAI. He has completed successfully several alternative fuel engine and vehicle projects for major OEMs.

He serves as a member in the expert committee on Alternative fuels of Department of Science and Technology (DST) and MNRE. He represents India on the ISO TC 22 and ISO TC 197 committees on gaseous fuel standards. He is the chairman of BIS TED-26 National Standards Committee on gaseous fuels. He is also a member of AISC and several national committees. He is the Governing Board Member of SAE India Western Section, life member of Combustion Institute and ISTE.

He has published 14 books and has six patents to his credit. He has numerous publications in national and international conferences and international journals. He has won three awards for best technical paper in international conferences.